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DESIGN OF COMPACT, LIGHTWEIGHT POWER TRANSMISSION DEVICES FOR SPECIALIZED HIGH POWER APPLICATIONS (POSTPRINT)

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Mechanical Energy Conversion Branch
Energy/Power/Thermal Division

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14. ABSTRACT
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Design of Compact, Lightweight Power Transmission Devices for Specialized High Power Applications

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ABSTRACT

The design of compact and lightweight power transmission devices was studied for specialized high power applications, including airborne with operating voltage fixed at 270 Volts and less than 30 meter length conductors. Only commercial-off-the-shelf components were considered for the design. It was found that by using superconducting wires operated at cryogenic temperatures instead of Cu conductors, a large increase of performance could be achieved; e.g. there is large reduction of heat loss; and for 5 MW-class or 20 kA power transmission there is a substantial reduction of weight of ~ 80/kg per meter and an approximate 10x reduction of volume. A strong reduction of weight is achieved for > 1000 Amp power transmission.

INTRODUCTION

The development of new electric conductors in the past 20 years with up to 200x higher power/volume capacity than standard copper conductors has created the potential to use these new conductors to improve the performance and efficiency of high-power current transmission systems. New materials with higher conductivity include doped carbon graphite or nanotubes, hyperconducting metal alloys, or advanced high temperature superconductors (HTS) with operation temperatures up to 80 K[1].

The development of improved power density devices for specialized applications including airborne is on-going[2]; however, the problems of electrical power transmission between these devices still need consideration. For example, the weight of power cables running from advanced airborne high-power generators is likely to exceed the generator weight, and heat losses of wires which are proportional to the increased device power levels can reduce system performance. To further improve high power device operation at 50 K to 300 K, the design and optimization of power transmission devices can reduce system heat loss and weight. While development proceeds on higher performance power transmission devices for commercial power industries[3-5], relatively little effort exists for optimizing the power transmission systems for low voltage operation and low AC frequency or DC systems typical for many specialized high power applications. Previously development of superconducting power lines for high voltage, high power operation (20-120 kV, 100-1500 MW) demonstrated 4-40x reduction of total system heat loss (including cryogenic) and an approximate 10x reduction of transmission cable size and weight compared to copper, for commercially viable systems[3].

Herein considers the design of electrical power transmission systems for specialized applications such as airborne. The basic research principles to study this problem have been well-established, as will be shown. However airborne applications have specific design criteria which have not always been considered in detail yet. For airborne applications, the operating voltage is typically fixed at V = 270 Volts because of many considerations including the need to minimize arc discharges at lower atmospheric pressures. It might be possible to engineer around this requirement with increased electrical insulation, however this possibility was not considered herein.

The output or operating power of a device is known from basic principles and Ohm's law as P = IV, where I is the current applied and V is the operating voltage. Therefore, to increase the power output substantially for airborne applications it is not practical to increase the operating voltage as is common for ground-based transmission systems, but only the operating current must be increased. This benefits device design by reducing the amount of electrical insulation, however causes different design problems to accomodate higher currents.

This paper studies the design of high power transmission lines and cryogenic current leads for low voltage (< 300 V) and DC or low-frequency AC (< 1000 Hz), and also short length < 30 meters which are useful for airborne applications. Although designing for any operation temperature can be considered, the emphasis herein is for operation temperatures of 50-80 K for compatibility with next-generation high-power applications including generators utilizing YBCO high temperature superconductor (HTS) wires[2,6]. The design of a system that demonstrates competitive system size, weight

and/or power loss reduction is a goal. For any high-power application, the development of refrigerated (or cryogenic) power transmission systems has potential if the system size, weight and power losses including refrigeration can be lower than comparable room-temperature copper or aluminum and solid-state components.

Preliminary results herein show that by using new generation high-temperature superconducting wire, similar reductions to high-voltage commercial-power systems can be realized for 5MW-class power transmission, giving substantial weight reductions of about 80 kg/m of wire compared to copper. Reduced power losses also are achieved, however the savings in weight is comparatively more substantial.

LONG LENGTH CONDUCTORS

While research and development of higher conductivity materials is on-going, there are relatively few conductor materials that have been successfully manufactured in long lengths ~ 0.5-1.0 km with reasonable cost and physical properties sufficient for commercial sales[1]. Wire manufacturing lengths ~ 1 km are needed, to assemble higher current cables carrying 10kA or higher of 10-30 meter length.

Figure 1 compares commercially available 400A-class Cu transmission wires that operate at-or-near room temperature to $YBa_2Cu_3O_{7-z}$ (YBCO) high temperature superconductor (HTS) wires that operate at 4-80 K. The YBCO wire is approximately 800x smaller in volume and weight than Cu, while carrying the same 400 A however at 77 K rather than room temperature. The equivalency is based on YBCO wires carrying critical current (I_c) = 1000 A/cm which have been achieved in short processing lengths of ~ 1 meter. Although improvements are rapidly being made, the performance of YBCO wires at the present state of manufacturing development goes down from this for longer length processing of ~ 950 m with I_c = 200A/cm, as shown in Fig. 2. Depending on the operation temperature and magnetic field, Fig. 2 shows that YBCO conductors processed in km lengths has higher current density compared to other conductors in fully engineered and manufactured conductors. Operation of YBCO wires at 77K for most applications is technologically achievable by using relatively small cryocoolers, as will be shown herein.

Operation of Cu wires at cryogenic temperatures is not practical for long durations, because the power loss from resistive heating with cryocooler inefficiency is too large a percentage of the power transported. In contrast the electrical resistance and power loss of YBCO wires at < 80K is practically zero for DC current transmission, so the only power loss for the transmission system is the cryocooler and vacuum component losses needed to maintain the cryogenic environment[4].

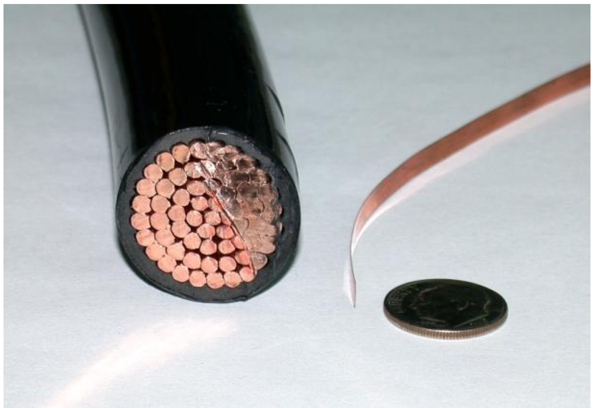
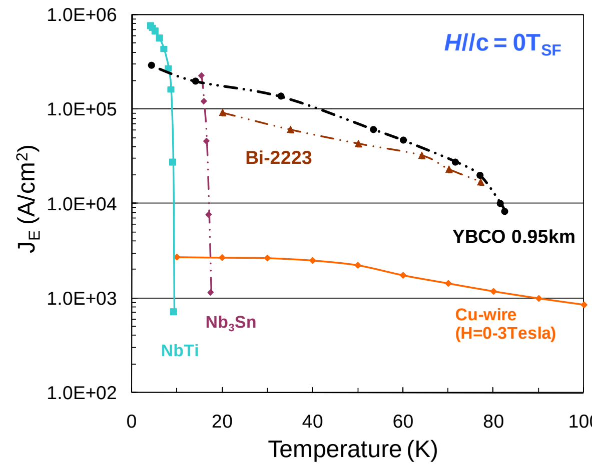


Figure 1. Commercially available 400A-class wires of Cu (left) and $YBa_2Cu_3O_{7-z}$ (YBCO) middle (at 77K operation temperature), compared in size to a dime. Interestingly, the superconducting volume of the YBCO wire which is ~ 0.4cmx0.01cm is ~1% of the volume shown, with the balance being ~0.005 cm thick metal-alloy substrate and ~0.005 cm thick copper layer for stabilization in case of quench. The volume and weight of this Cu wire compared to YBCO is ~ 800:1, and the ratio for comparing multiple 2/0 Cu wires with 400 A capacity to YBCO is ~ 400:1.



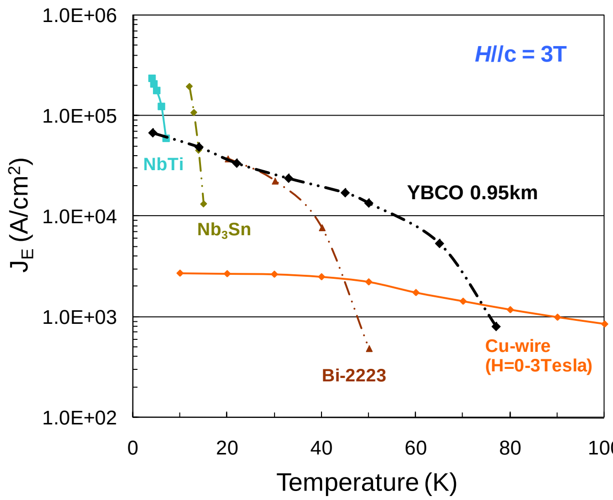


Figure 2. Engineering current density of km-length commercially available superconductors wires,

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compared to standard Cu wires that function in self or high magnetic fields[7-10]. The dependence on temperature is shown, for applied fields in the worst orientation of H//c-axis with magnitudes of 0 Tesla (self-field) which is used for power transmission, and 3 Tesla which is typical for many power applications. Superconductors are low temperature NbTi and Nb_3Sn, and high temperature $YBa_2Cu_3O_{7-z}$ (YBCO) and $(Bi,Pb)Sr_2Ca_2Cu_3O_{10-z}$ (Bi-2223). The quality of YBCO manufacturing is continually improving, and the J_e values are shown as of July 2008.

SYSTEM THERMAL HEAT LOSS

The system thermal heat loss (Q_s) of an electrical power transmission system depends on a number of components, and can be written as

$$Q_S = \xi_{CR}*(Q_{CD} + Q_{VT} + Q_{CL}), \qquad (1)$$

where ξ_{CR} is the efficiency of the cryocooler if used, Q_{CD} is the heat loss of the conductor, Q_{VT} is the heat loss of the vacuum tubing if used, and Q_{CL} is the heat loss of the current leads into and out of the power transmission system which can be significant if the system is operated at refrigerated temperatures.

In the following sections, the specific heat losses are described in detail.

POWER LOSS OF CONDUCTORS – The power loss of the conductors are described in the following.

Power Loss of Resistive Conductor - The power loss of resistive conductors such as copper or aluminum is known from Ohm's law as

$$Q_{CD} = P = I^2R \qquad (2)$$

where R = ρL/A is the resistance of the conductor, with ρ = resistivity, L = wire length, and A = wire cross-sectional area. The square dependence on current creates additional problems for airborne applications, and suggests there is a need to greatly reduce R as much as possible to minimize heat losses. The only alternative to reducing the resistance is to reduce the operation time to reduce the energy loss for a given time. The resistance of copper cables of different designs including Litz wire for AC operation are quantified by commercial manufacturers, and are freely available[11].

Power Loss of Superconducting Cables: AC - The power loss of superconducting cables for AC transmission has been studied in great detail, and the principles to reduce and control heat losses are understood from theory and modeling[12-16]. A critical factor to lower AC loss is to reduce exposing the tape to perpendicular magnetic field components as much as possible, which has a much larger effect than parallel magnetic fields[12]. The AC power loss can be reduced to very low levels by considering and optimizing cable geometries, and by reducing operation temperature and filament width. In general, as the current level increases the cable size must increase significantly to minimize exposing individual conductors to perpendicular magnetic fields. Figure 3 plots both measured and theoretical AC losses for different cable designs. It is seen in Fig. 3 that to increase the currents from 1kArms to 10kArms and keep losses < 1 W/m, the diameter of the cable should be increased from ~ 2 cm to ~ 9 cm. Each AC wire design has particular parameters that change the dependence, however in general the cable diameter must be increased with current capacity to keep AC losses at very low levels such < 1 W/m.

Also Fig. 3 shows that for a given design, the heat loss generally grows exponentially with increasing current above the designed-for current.

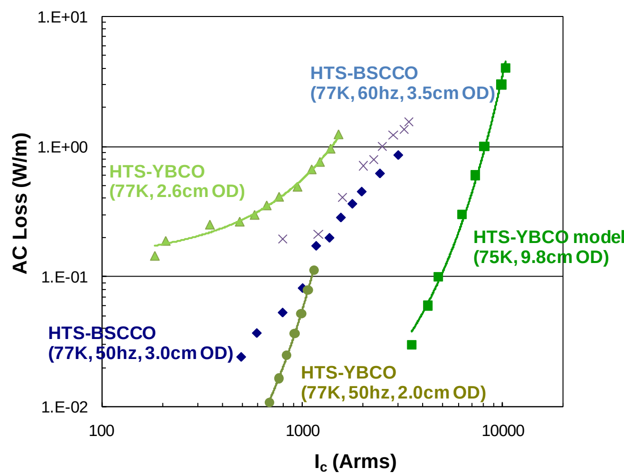


Figure 3. AC loss of high-temperature-superconductor cables: ● Amemiya[12] ▲ Gouge[14] ■ Rastila[16] ♦ Kimura[13] and x Sytnikov[15]. Lines shown are exponential fits.

Power Loss of Superconducting Cables: DC - The design of high current superconducting cables for DC transmission is simpler than for AC transmission, however also depends on geometrical factors to minimize reduction of I_c from self-field magnetic effects[4]. Not accounting for self-field reductions or losses from harmonics which can be important for ground-based long length power transmission[5], the DC loss is calculated with the simple formula P = IV and rewriting using the electric field

$$P = IV = IEL \qquad (3)$$

where I is the current, E is the electric field, and L is the wire length. The electric field of YBCO HTS coated conductor wires is shown in Table I, which shows very low electric field until the current exceeds the 'critical current' value defined roughly using the critieria of E = 1 μV/cm. Table I shows that it is possible to operate HTS wires with almost immeasurably low electric fields even in magnetic fields, and therefore the power loss calculated from Eqn. 3 is very low even with very high currents or long wire lengths. As an example, for high power applications with I = 20 kA and L = 10 meters, the power loss can be reduced below 10^{-3} Watts by choosing the correct operation current. So for most practical

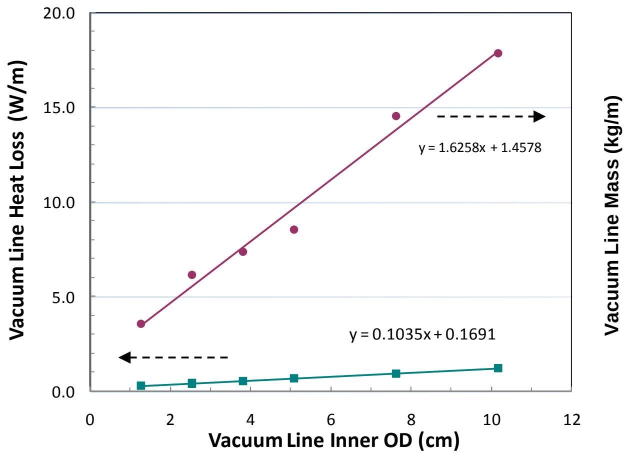
situations, the DC power loss of superconductors is ~ zero. The use of HTS DC cables for long length power transmission has been studied, and the efficiency for 1GW class systems increased from ~80% for Cu to ~95% using HTS wires and cryocooling, realizing a savings of ~ 150 MW[4]. The heat losses of these HTS DC power transmission cables were almost entirely from cryogenic refrigeration, rather than resistive heating of the conductor[4].

Table I. Electric field values at 77K of YBCO HTS coated conductors in DC fields for varying current and applied magnetic fields[17].

Electric Field (V/cm)	I/w (A/cm) @ $\mu_o H = 0$ T	I/w (A/cm) @ $\mu_o H = 0.1$ T	I/w (A/cm) @ $\mu_o H = 0.2$ T
10^{-5}	661	384	266
10^{-6}	611	338	232
10^{-7}	572	291	196
10^{-8}	559	259	175
10^{-10}		247	160
10^{-11}		229	147
$2x10^{-12}$		215	139

POWER LOSS OF CRYOGENIC VACUUM COMPONENTS - The heat losses of commercial-off-the-shelf (COTS) cryogenic vacuum components are given by the manufacturers, and listed in their literature or websites. Specific cryogenic vacuum heat pipe components and their heat losses are shown in Fig. 4, from Quality Cryogenics and PHPK Technologies[18,19]. Bayonets and field joints typically have heat losses 4-6x and 3-4x higher than rigid pipes, respectively[19]. The precise engineering of components affects the losses, and there are tradeoff issues in the designs that can affect the heat losses, sizes and applicability in different systems. For example, Figure 4 shows it is possible to use flexible vacuum lines instead of rigid lines which increases the heat losses by about 3x, however makes it easier to apply in certain applications. As another example in Fig. 4, the vacuum heat pipes can be reduced in outer diameter, however the heat losses will increase slightly.

Inner Pipe OD (NPS[18])	Outer Jacket OD (NPS[18])	Rigid Pipe Heat Loss (W/m)	Flex Pipe Heat Loss (W/m)	Pipe Mass (kg/m)	Ref
½”	2”	.31		3.6	19
¾”	1 ¼”	.36	.92		18
¾”	2”	.43	1.15		18
1”	2 ½”	.46	1.38		18
1”	3 “	.43		6.2	19
1 ½”	3 ½”	.54		7.4	19
2”	4”	.72		8.6	19
3”	5”	.94		14.6	19



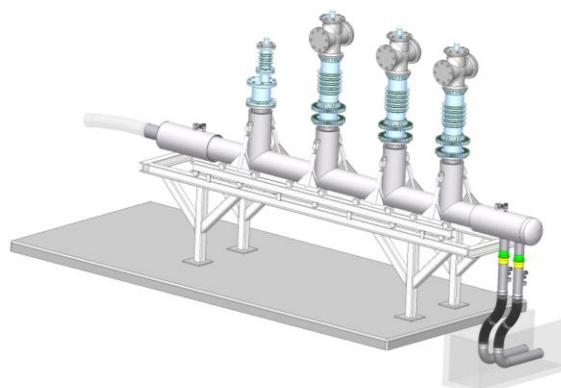


Figure 4. Heat losses at 77K and masses of cryogenic components, manufactured by PHPK Technologies[18] and Quality Cryogenics[19]. The middle figure plots heat loss and mass from tabular data by Quality Cryogenics[19]. A termination image is provided courtesy of PHPK Technologies[18].

POWER LOSS OF HIGH CURRENT LEADS - The DC losses of high current leads of have been studied in great detail, for present and future application in large particle accelerators such as the Large Hadron Collider (LHC), or fusion magnet power devices such as large helical devices (LHD)[20]. For the LHC application, total currents up to 1.7 MA will be required and much consideration of methods to reduce heat losses are being considered[20]. Thousands of current leads have been built and tested, to determine optimal designs[20]. For conventional leads operating between room temperature and 75K, the total heat losses if a cryocooler is used is < 250 W/kA which is quite high[21]. A very large cryocooler would be required for 20kA, which might not be practical for some applications. This suggests the application of HTS might be limited to applications where power is generated and consumed at cryogenic temperatures, however this is not completely studied yet.

The losses for current leads depend on design factors, and in particular the voltage levels. As the voltage levels increase to increase the power transmission levels, the

electrical insulation must be stronger and larger which increases the heat losses of the current leads. So optimum design of current leads depends on specifying the voltage and other operation parameters such as operating temperature[22].

TOTAL SYSTEM HEAT LOSSES

The total system losses for only the power transmission devices are calculated for different current levels as shown in Fig. 5. The losses in Fig. 5 do not include current leads or other vacuum components such as joints or bayonets, which are application-dependent. Also the exact design of a DC cable has not been fully considered, and issues and effects such as magnetic shielding, dielectric insulation, and cooling liquid or gas flows and design apparatus have not been considered yet. A cryocooler efficiency of ~16.5 for piston-free Stirling cryocoolers available from Sunpower is used for Fig. 5[23]. In Fig. 5 for AC loss of 50 hz, a 2.0 cm wire design by Amemiya with OD ~ 2.0 cm [12] was used for I ≤ 1 kA, and for I ≥ 2 kA a 3.0 cm wire design by Kimura[13] was used. Different AC wire designs are possible, and AC losses can be minimized further; e.g. with smaller filament widths. However Fig. 5 shows the initial results using these already established AC wire designs.

In Fig. 5, the heat losses are minimally low for DC application of superconductors, and for AC application the losses are still considerably lower than Cu. The AC system loss for superconductor wires only becomes different from DC when the design of the wire becomes larger and AC loss of the conductor becomes larger than the heat loss of the cryogenic piping $Q_{CD} > Q_{VT} \sim 0.5$ W/m (from Fig. 4). The heat losses for Cu wire begin to become significant for current levels above ~ 10 kA, producing 500 W per meter. The heat loss of the HTS wire in DC operation is entirely from the inefficiency of the cryogenic vacuum components and cryocooler. However Fig. 5 shows system heat loss for large current transmission in HTS DC mode can be extremely low; e.g. for current levels of 30 kA only 100 W of total system heat loss are produced for 10 meter system length. This is amazingly low, and the transmission is > 99.999% efficient.

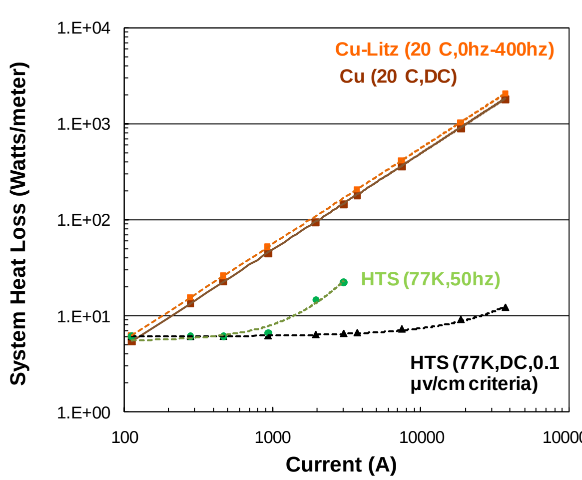


Figure 5. System heat loss including conductors, cryogenic vacuum tubing with size 1”-1¼” outer OD for HTS DC and 1”-2.5” outer OD for HTS 50 hz, and cryocooler efficiency. The system does not include current leads or other vacuum components such as joints or bayonets, which are application-dependent. Heat loss for Cu wires were calculated using the resistivity of commercial 2/0 wire[11]. Loss of the HTS system for I ≤ 1 kA uses 2.0 cm design from Amemiya[12], and for I ≥ 2 kA uses 3.0 cm design by Kimura[13].

TOTAL SYSTEM MASS

The total system mass was calculated as shown in Fig. 6, which includes the mass of the conductor, 2” outer OD vacuum piping, and cryocooler. As Fig. 6 shows, at a crossover point of I = 1 kA the system mass of the superconducting system is increasingly smaller compared to the Cu wire system. The crossover point for DC current could be reduced by designing using vacuum tubing with smaller outer OD or made of lighter materials. For large current and power levels (I = 18.2 kA and P = 5MW), the mass is almost 20x higher for Cu than HTS systems, and the weight savings begin to become significant; 400kg or close to ½ ton compared to 20kg. Any reduction of weight on airborne systems has a benefit 5-10x greater since lower fuel and space loads are realized. The weight improvements for HTS DC wires shown in Fig. 6 become larger with higher currents or increasing wire lengths. Similar reductions of weight ~ 10x have been achieved for high power level conductor systems for commercial power transmission of ground b

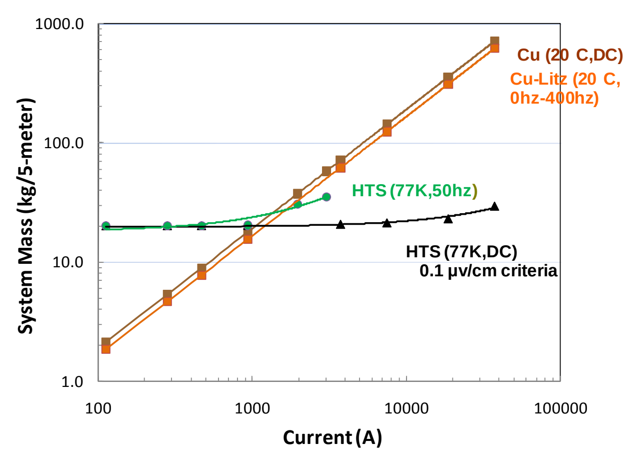


Figure 6. Mass of typical 5-meter length systems, which includes conductor, cryogenic vacuum tubing with size 1”-1¼” outer OD for HTS DC and 1”-2.5” outer OD for HTS 50 hz, and cryocooler. The HTS system mass does not include current leads or other vacuum components such as joints or bayonets, which are application-dependent. Mass for Cu wires were calculated using the density of commercial 2/0 wire[11]. The mass of Stirling cryocoolers needed for adequate cooling was used[23].

TOTAL SYSTEM VOLUME

The system volume is calculated for different designs, as shown in Fig. 7. To calculate Fig. 7, the different vacuum piping to accommodate both AC and DC wire designs were used, as given in Fig. 3. The volumes of commercially available Stirling cycle refrigerators with small size of 7-8 cm outer-diameter and 24-26 cm length were used for the cryocooler volume[23]

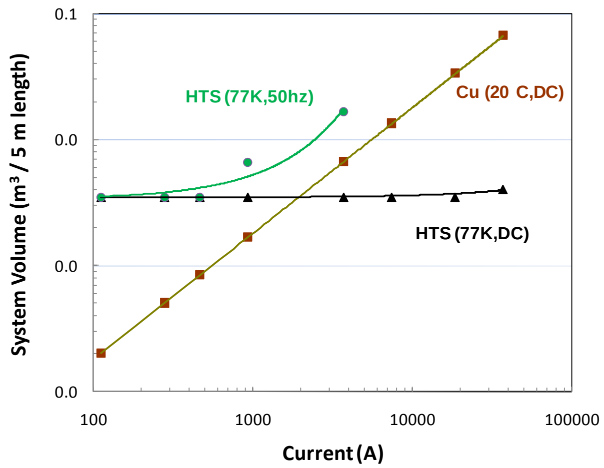


Figure 7. Total volume of typical 5-meter length Cu wire and HTS systems which includes conductor, cryogenic vacuum tubing with size 1"-1¼" outer OD for HTS DC and 1"-2.5" outer OD for HTS 50 hz, and cryocooler. The HTS system volume does not include current leads or other vacuum components such as joints or bayonets, which are application-dependent. System volume for Cu wires were calculated using the density of commercial 2/0 wire[11].

Above about 2000 A, the HTS volume for DC power transmission begins to have significant advantages, while the HTS AC system has the largest volume because of the design needed to minimize AC losses from perpendicular magnetic fields. The crossover point for DC power transmission to provide advantage could be lowered below 2000 A, by designing with smaller outer OD vacuum tubing.

CONCLUSION

The design of compact and lightweight power transmission devices was accomplished using commercial-off-the-shelf (COTS) parts for specialized high power applications, including airborne with operating voltage fixed at 270 Volts and less than 30 meter length system. The preliminary design showed that for currents exceeding 1-2 kA, about 50-100 times reduction of system weight, heat loss and volume could be achieved utilizing high temperature superconductor wire and cryogenic-cooled systems, compared to traditional copper conductors. These advantages were realized operating in DC mode. When operating in AC mode, reductions of system heat loss and mass could be achieved with the HTS system, however the volume became larger than Cu wires. This was because of the need to minimize AC heat loss from exposure of wires to perpendicular magnetic fields. Results for AC frequencies are very dependent on the properties and design of the wire and the specific operation conditions, and further study of the system design and tradeoff issues are needed.

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